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Propulsion Systems Survey for the USCG Deepwater Surface Platform

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16. Abstract (Maximum 200 words)

Proteus Engineering was tasked by the Marine Systems and Environmental Technology Division, U.S. Coast Guard Research and Development Center, to investigate propulsion systems that may be candidates for the Coast Guard's Deepwater Surface Platform. This report summarizes the findings of the investigation.

The U.S. Coast Guard is in the concept exploration phase of its Deepwater Capabilities Replacement project. This project will define the next generation of surface, air and command, control, communications, computers, intelligence, sensors, and reconnaissance (C4ISR) assets used to perform the Coast Guard's missions in the Deepwater environment (greater than 50 NM off the U.S. coastline). As part of early technology investigations, the Project Manager has a requirement to understand surface ship propulsions systems technology that will be functionally available and proven by 2002.

The vast majority of ships and patrol boats with similar mission profiles to the Deepwater Surface cutter(s) are powered by combined diesel/gas turbine plants, driving controllable-reversible pitch propellers through reduction gears. With the exception of fuel cells, few technologies are likely to appear as candidates in 2002 that are not proven now. However, a number of currently operating propulsion system components that would be new to the Coast Guard, such as waterjets, podded propulsors, and AC electric drives, are candidate technologies.

Propulsion systems are broken down into propulsors, transmissions, and power sources. The impact of the propulsion system design on mission and operational requirements, hull form alternatives, and life cycle cost are addressed.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
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lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
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yd^3	cubic yards	0.76	cubic meters	m^3
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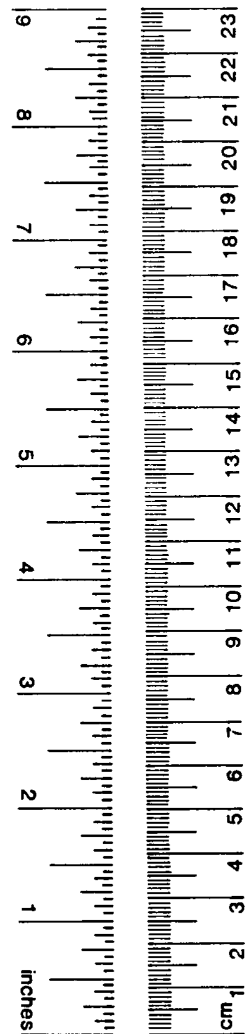
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

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cm	centimeters	0.4	inches	in
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m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
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kg	kilograms	2.2	pounds	lb
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		VOLUME		
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l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
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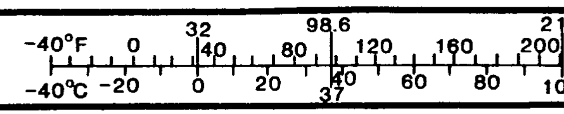

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EXECUTIVE SUMMARY

The U.S. Coast Guard is in the Concept Exploration Phase of its Deepwater Capabilities Replacement Project. This project will define the next generation of surface, air and command, control, communications, computers, intelligence, sensors, and reconnaissance (C4ISR) assets used to perform the Coast Guard's missions in the Deepwater environment (>50 NM off the U.S. coastline). This report presents a high-level survey of surface ship propulsion systems technology that will be functionally available and proven by 2002.

Combined diesel/gas turbine plants power the vast majority of ships and patrol boats with similar mission profiles to the Deepwater Surface cutter(s), driving controllable-reversible pitch propellers through reduction gears. With the exception of fuel cells, few technologies are likely to appear as candidates in 2002 that are not proven now. However, a number of currently operating propulsion system components that would be new to the Coast Guard, such as waterjets, podded propulsors, and AC electric drives are candidate technologies.

In this study, propulsion systems are broken down into propulsors, transmissions, and power sources. System attributes are described on data sheets. Mission and operational impacts, hull form impacts, and life-cycle impacts of system selections are also described.

A Microsoft Excel model was also developed to assist in analyzing the variety of propulsion system options. The model can quickly calculate rough estimates of annual fuel consumption, system space claim, and weight claim. Although the model is described in this report, it was developed for Coast Guard in-house use only.

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INTRODUCTION

The purpose of this report is to evaluate the suitability of existing surface vessel propulsion systems and those that are likely to be functionally available and proven by 2002 for the Coast Guard's future Deepwater surface platform(s). The report is not intended to recommend a specific system, but to point out the advantages and disadvantages of candidate systems. Candidate systems were identified in Task A of this delivery order, this report (Task B) provides performance and other system attributes of interest to the Coast Guard.

CURRENT SYSTEMS

Present Coast Guard Deepwater surface assets are: 378' High Endurance Cutters, 270' Medium Endurance Cutters, 210' Medium Endurance Cutters, 'Mature Class' Medium Endurance Cutters, and 110' Island Class Patrol Boats. Propulsion Systems on those cutter classes are as follows:

> 378' WHEC - Twin CODOG, non-reversing reduction gears, controllable-reversible pitch propellers.
>
> 270' WMEC - Twin diesels, non-reversing reduction gears, controllable-reversible pitch propellers.
>
> 210' WMEC - Twin diesels, non-reversing reduction gears, controllable-reversible pitch propellers. Note: The "A" Class 210's were originally designed as a CODAG plant.
>
> 'Mature Class' WMEC - Three or four diesel engines driving DC generators to DC motor(s) driving one propeller directly or two propellers through non-reversing gears.
>
> 110' WPB - Twin high-speed diesels, reverse reduction gears, fixed pitch propellers.

Other cutter propulsion systems in the current Coast Guard inventory:

> Polar Class Icebreakers - Diesel electric combined with geared gas turbines turning controllable-reversible pitch propellers.
>
> 180' WLM - Twin diesel DC generator sets, single DC propulsion motor directly coupled to a fixed pitch propeller.
>
> USCGC HEALY - 4 diesel AC generator sets feeding propulsion and ship service power, cycloconverter system to two AC motors directly coupled to fixed pitch propellers.
>
> 'JUNIPER' Class WLB - Twin diesel engines driving a single propeller through a combining reduction gear.
>
> 'KEEPER' Class WLM - Twin diesel engines, each driving a Z-drive propulsor.

NEW SHIP CONSTRUCTION PROGRAMS

The overwhelming majority of new construction or recently commissioned frigate sized ships worldwide are, or will be, powered by Combined Diesel or Gas Turbine (CODOG) plants with one or two gas turbines combined with two diesel engines through a non-reversing reduction gear driving twin shafts, each with controllable pitch propellers. Top speeds for these ships are typically 30 knots. Representative frigate new construction/design programs are: ANZAC (MEKO 200) Class (Australia, New Zealand), LA FAYETTE Class (France), BRANDENBERG Class (Germany), KDX-2 and OKPO Classes (South Korea) and HYDRA Class (Greece). [1]

The only exceptions to a CODOG plant among new or recently constructed frigates are the United Kingdom's Type 23, which has a Combined Diesel Electric and Gas Turbine (CODELAG) plant and the French LA FAYETTE Class, which is Combined Diesel and Diesel (CODAD).

Among corvette and patrol boat sized ships there is a broader range of power plants represented, with CODOG, CODAG and multiple diesel installations driving fixed or controllable pitch propellers or waterjets through reduction gears. Examples of recent or new construction programs and their drive train combination are: FLYVEFEISKEN Class (CODAG, 3 shafts - Denmark), AL MANAMA (4 diesels, 4 shafts - Bahrain), SAAR-5 (CODAG, one turbine, two diesels, two shafts - Israel), NGPV (Diesel electric - Singapore), and VISBY (CODOG - Sweden). [1]

PROPULSION SYSTEMS

For ease of evaluation, propulsion systems are considered using a modular approach. The overall system is broken down into propulsors, transmissions and power sources. This allows a 'mix and match' approach to system evaluation by selecting compatible sub-systems from each category. A typical propulsion system design approach would start once the effective horsepower required for the ship is known. From that point, hull form and arrangement constraints, projected operations profile, maneuvering requirements, specific mission needs, weight budget, and overall system design criteria all factor in to selecting the best propulsion system. Systems considered in Task A are summarized in Table 1, including whether or not they were carried forward for further evaluation. A 'Y' indicates a system that was carried forward for further consideration, an 'N' indicates a system that was not considered to be a viable candidate for a Deepwater cutter(s).

Table 1 – Candidate Propulsion Systems

Propulsors		**Transmission Systems**		**Power Sources**	
Fixed Pitch Propeller	Y	Reversing Gears	Y	Low Speed Diesel	N
Controllable Reversible Pitch Propeller	Y	Non-Reversing Gears	Y	Medium Speed Diesel	Y
Contra-Rotating Propeller	Y	AC/AC Electric	Y	High Speed Diesel	Y
Supercavitating Propeller	N	AC/DC or DC/AC Electric	N	Gas Turbine	Y
Surface Piercing Propeller	N	Direct Drive	Y	Combined Plants	Y
Vertical Axis (Cycloidal) Propeller	N	Z-Drive	Y	Fuel Cell	Y
Waterjet	Y			Integrated Electric Drive	Y
Pump Jet	Y			Steam Turbine	N
Podded Propulsors	Y				

Tables 2 and 3 show compatibility of the various system component candidates. Combinations which are technically feasible, but would add redundant capability are not shown as compatible. For example, controllable-reversible pitch propellers could be matched with reversing gears, but the addition cost and complexity of the reverse gear mechanism adds no value to the system since the propeller is reversible.

Table 2 – Propulsor/Transmission Compatibility Matrix

Propulsor / Transmission	**Reversing Gears**	**Non-Reversing Gears**	**AC/AC Electric**	**Direct Drive**	**Z-Drive**
Fixed Pitch Propellers	X		X		X
Controllable-Reversible Pitch Propellers		X	X		
Contra-Rotating Propeller	X		X		X
Waterjet	X	X	X	X	
Pump Jet		X	X	X	
Podded Propulsors			X		

Table 3 – Transmission/Power Source Compatibility Matrix

Power Source / Transmission	**Reversing Gears**	**Non-Reversing Gears**	**AC/AC Electric**	**Direct Drive**	**Z-Drive**
Medium Speed Diesel	X	X	X	X	X
High Speed Diesel	X	X	X	X	X
Gas Turbine	X	X	X		
Combined Diesel or Gas (CODOG)	X	X			
Combined Diesel or Diesel (CODOD)	X	X			
Combined Diesel and Diesel (CODAD)	X	X			
Combined Diesel and Gas (CODAG)	X	X			
Combined Gas or Gas (COGOG)	X	X			
Combined Gas and Gas (COGAG)	X	X			
Combined Diesel Electric and Gas (CODLAG)	X	X	X		
Fuel Cell			X		
Integrated Electric Drive			X		X

The combined diesel electric gas turbine (CODLAG) is a special case since both electric drive (with the diesel generator) and gear drive (with the gas turbine) are

used. The weight and space claim for the combination transmission is accounted for in the system model's calculations.

An integrated electric drive could utilize a combination of electrical power sources, for example fuel cells combined with diesel or gas turbine generator sets.

PROPULSORS

Conventional Fixed-Pitch (Screw) Propeller

The most common propulsor in use. Consists of two or more lifting surfaces, known as blades, extending radially from a common base called the hub. The blades are "pitched" about their own radial axes in order to give them an angle of attack relative to the local flow and hence allowing them to generate a thrust-producing lift force. Blades are fixed relative to the propeller hub.

Controllable-Reversible Pitch (CRP) Propeller

Same as a fixed-pitch propeller, but the blades can be rotated to vary the pitch of the propeller changing the load characteristics. In this way a more optimum pitch can be achieved over a wider range of operating conditions than for fixed-pitch propellers. The pitch can also be reversed to provide reverse thrust without changing the direction of shaft rotation.

Contra-Rotating Propeller

Two propellers on a coaxial shaft, rotating in opposite directions. The counter rotation captures some of the swirl energy imparted to the water that would otherwise be lost in the wake. The trade-off to the higher efficiency is higher mechanical complexity, increased weight and increased cost.

Waterjet

A waterjet is essentially an axial or mixed flow pump mounted internal to the ship's hull. At speeds below approximately 25 knots, a waterjet is generally less efficient than conventional propellers. However, the lack of appendages reduces drag and vessel draft. The jet exit is typically fitted with steering/reversing buckets eliminating the need for rudders or a reverse gear.

The power curve of a waterjet is dependent primarily on shaft RPM, with very little dependence on ship speed. This characteristic may make them a good choice for combined drive applications where each prime mover drives its own shaft.

Pump Jet

A centrifugal pump mounted horizontally. The jet outlet typically rotates to provide thrust in any direction. Pump jets are flush mounted and relatively efficient. Pump jets are larger and heavier than waterjets. The top power range available is approximately 4000 hp. They may be candidates for a small cutter propulsion system if top speed is limited to the high teens/low 20 knot range

Podded Propulsors

A podded propulsor is a propeller, or sometimes two propellers, which may be contra-rotating, driven by an electric motor. The motor is mounted in a pod external to the hull. The pod can be rotated to provide thrust in any direction, eliminating the need for rudders. Other performance characteristics would be similar to propellers. The system is similar to a Z-drive.

Other Devices

A number of ducts, vanes, fin systems, or other methods of recapturing the energy a lost to propeller swirl or improving flow through the propeller are available on the market. These devices improve propulsion efficiency by capturing otherwise lost energy at the expense of weight, system complexity and acquisition cost. Ducted propellers, in particular, offer significant propulsor efficiency improvements in conditions of heavy loading and slow speed such as when towing other vessels, and many can be designed to have minimal adverse performance impacts at free-running conditions.

TRANSMISSIONS

Reversing Gears

A gear set which takes the input from the main power source and reduces the output speed to match the propulsor requirements. There may be multiple inputs to a single output, a single input to a single output, multiple inputs to multiple outputs, or a single input to multiple outputs. They include the capability of reversing the output direction.

Gears are compact, efficient, typically over 98% [2], reliable and well proven in marine applications. The primary disadvantages are: a lack of arrangement flexibility since all drive train components must be arranged in alignment and in a multiple engine setup, the fixed gear ratio will only allow the power curve of the engine(s) to be optimized for one running configuration. [3]

Non-Reversing Gears

Same as reversing gears, but without the reversing capability. An installation with non-reversing gears would have a controllable-reversible propulsor or reversible engine. None of the candidate engine technologies carried into this phase of the study are reversible, so any proposed Deepwater surface cutter with a non-reversing gear drive would be expected to have a controllable-reversible propeller. Note that in some electric drive applications, a reduction gear is used with the motor(s) to allow the use of more compact, higher speed motors.

AC/AC Electric

AC generator set(s) provide propulsion power to AC motors that are either directly coupled to the propulsor or connected through reduction gears. Speed control is provided through frequency conversion circuitry, the three leading types are cycloconverter, load-commutated inverter and pulse width modulated. The U.S. Navy is sponsoring significant research into the power electronics needed for control and conversion of electric power for propulsion and ship service use.

It is common to provide ship service power from the ship's propulsion buss in these systems. By feeding ship's service and propulsion power from a common source, the total number of generator sets aboard ship can be reduced, lowering acquisition and maintenance costs. Also, the larger propulsion engines tend to be a more efficient source of power than the smaller engines typically selected for ship service generators, especially at the differential fuel rate for adding additional load to an operating engine.

Since there is no fixed alignment between the engine and the propulsor, an electric drive plant also offers significant advantages in arrangement flexibility.

Direct Drive

The engine is directly coupled to the propulsor. Direct drive is possible only when the power curve of the engine is compatible with the demand curve of the propulsor. Low speed diesels are typically connected directly to the propeller shaft. Other applications where direct drive is possible are waterjets, high speed propulsor variants, and pumpjets. Because there is no reversing mechanism in the transmission, either the engine needs to be reversible (as in low speed diesels) or the propulsor needs to have a reversing capability.

Z-drive

A Z-drive is an angled propulsion system consisting of a double right angled gear train driving a propeller. Some applications enclose the propeller in a duct. Fore and aft propellers with vanes mounted on the drive to capture swirl energy are also installed in some drives. By incorporating gear reduction in the gear train, a Z-drive is able to function as a combined propulsor and transmission. Because of the vertical shaft segment, the drive can be rotated to vector thrust in any direction, eliminating the need for rudders and reversing gears.

POWER SOURCES

Medium Speed Diesel

Diesel engines operating in the range of approximately 300 to 1200 RPM. The speed range varies among sources, reference [2] contains a table showing 700 RPM as the lower range for medium speed diesels, but then discusses engines operating in the 300 - 514 RPM range. In general, the speed range used to classify an engine as high, medium or low speed is unimportant. What is important to recognize is that with increasing operating RPM, the power density of an engine, as measured by weight per horsepower or by volume per horsepower, generally increases, fuel efficiency generally decreases and maintenance costs generally increase.

Most medium speed diesels are adapted from industrial, stationary power generation, locomotive or other non-marine uses. Because most of these engines are also used as generator sets, the operating RPMs are often a divisor of 3600 RPM (i.e. 1200, 900, 720, ...300). These engines are not normally reversible so other means of reversing must be employed.

High Speed Diesel

High speed diesels cover the operating range above 1200 RPM. Again, different sources may use different dividing lines between the engine classifications. High speed marine diesels are usually available in a wide range of ratings and power outputs for the same engine because of their many applications. Manufacturers will usually have at least three, and often more, ratings for high speed diesels, a performance, or recreational use rating, an intermittent or crewboat rating, and a continuous rating. When comparing high speed diesels, it is very important to compare engines from different manufacturers at comparable ratings. For any vessel to be used in the Deepwater mission area, a continuous type rating would be appropriate. Other comments from the medium speed diesel discussion apply to high speed diesels as well.

Gas Turbine

Marine gas turbine engines are adapted from aviation or industrial power applications. They offer the highest power densities of any of the possible power sources for a vessel. The disadvantages of gas turbine engines are higher specific fuel consumption, particularly at partial loading, and increased acquisition costs as compared to diesel engines. Gas turbines have been the predominant propulsion power selection for naval combatant vessels over the past 20 years. Gas turbines are a popular power choice for high-speed ferries and other vessels where high power density is a requirement. Gas turbine power plants are normally configured as part of a combined power plant to allow operators the flexibility to avoid the poor fuel efficiency of part power operation.

The U.S. Navy is developing an intercooled-recuperated (ICR) gas turbine for marine propulsion that promises fuel economy approaching that of a diesel. The program recently completed a 500 hour endurance test [4] and is expected to provide approximately 27 percent savings in fuel consumption compared to conventional simple cycle gas turbines. The weight and space claim of an ICR turbine is roughly double that of a simple cycle turbine, with acquisition costs projected to be on the order of 50 - 100% higher.

Other considerations in selecting gas turbines include routing of intakes and exhausts. Although the engine itself is very compact, the airflow requirements of a turbine can involve extensive intake and exhaust piping and plenums, particularly if long runs to weather are involved.

Because they are not reversible, gas turbines need to have controllable-reversible pitch propellers, a waterjet with reversing capabilities, reverse reduction gear in the drive train, or an electric reversible transmission.

Combined Diesel or Gas (CODOG)

A system with a diesel engine and gas turbine connected to the propulsion shaft(s) through reduction gears. The most common system is a diesel and gas turbine for each propeller shaft, with controllable-reversible pitch propellers. Some systems have a single turbine driving both shafts through a gear box. The system is configured so the diesel(s) and turbine(s) do not operate at the same time, allowing the power curve and engine demand curves for each engine to be matched independently.

Combined Diesel or Diesel (CODOD)

The same concept as CODOG, but the high power engine is also a diesel. This concept would make sense for a ship that spends a significant amount of time loitering at speeds below the lower operating limit of the large diesel.

Combined Diesel and Diesel (CODAD)

Multiple diesel engines are connected to the propeller shaft(s) through a combining gearbox. CODAD plants are typically used when a single engine does not provide enough power, or when loitering operations would cause a single engine to operate below its lower operating range. Since all engines are intended to be operated together, the gear ratios selected will not be optimum for single engine operation [3], therefore CODAD installations typically use controllable-reversible pitch propellers to adjust the propeller demand curve for single engine operations.

Combined Diesel and Gas (CODAG)

CODAG is a similar concept to CODAD and CODOG, with a diesel engine and gas turbine connected to each propeller shaft. It differs from CODOG in that the diesel and gas turbine operate at the same time, presenting the problem of selecting a gear ratio that is sub optimum for single engine operations.

The systems generally have the diesel and gas turbines connected to the propulsion shaft through a combining gear box, although some installations are set up with the gas turbines and diesels each driving their own propeller shaft. For example, two outboard diesel driven shafts and a centerline shaft driven by a gas turbine.

Combined Gas or Gas (COGOG)

A system with two gas turbines connected to the propulsion shaft(s) through reduction gears. The system is configured so both turbines do not operate at the same time, allowing the power curve and engine demand curves for each engine to be matched independently. The system is similar to CODOG, except the cruise engine is a smaller turbine rather than a diesel.

Combined Gas and Gas (COGAG)

COGAG is a similar concept to CODAD and COGOG, with two gas turbines connected to each propeller shaft. It differs from COGOG in that the both gas turbines operate at the same time, presenting the problem of selecting a gear ratio that is sub optimum for single engine operations. The system is similar to CODAD, except both engines are turbines.

Combined Diesel Electric and Gas (CODLAG)

Similar to CODAG, but the shaft is driven by an electric motor for cruise/low speed operations. Because the speed-torque characteristics of a motor are variable, the power curve mismatch problems inherent in CODAG, CODAD and COGAG can be substantially eliminated.

Fuel Cell

Fuel cells operate similar to a battery, but do not require recharging. They electrochemically combine fuel and oxygen to produce electricity and water. There are four major types of fuel cells under consideration for marine power applications (Phosphoric Acid, Molten Carbonate, Solid Oxide, and Proton Exchange Membrane), all are potential candidates for providing shipboard electrical power for either propulsion or ship's service. Fuel cell technology, particularly fuel reformation, is not fully matured for shipboard application at this time, but may be by 2002. A fuel cell demonstration project is planned on the USCGC VINDICATOR.

Fuel cells offer efficiencies significantly better than diesel engines, with very low noise and low emissions. Some of the technological hurdles with integrating fuel cells into a ship's propulsion system are reforming diesel fuel for use in the fuel cell, handling varying loads and dealing with moist, salt air.

Although fuel cells are very low maintenance, they do have a finite life span of approximately 40,000 hours, at which time they must be replaced. With current technology, fuel cell systems have acquisition costs of roughly 5-6 times that of diesel power plants.

The power density varies with the type of fuel cell system selected. Fuel cells power density runs from roughly comparable to a medium speed diesel generator set ranging up to 2-3 times the space and weight claim of a medium speed diesel generator set.

The automobile industry is working to develop fuel cell technology with estimates of production fuel cell powered cars entering the market by 2004 [5]. Technologies improving life, efficiency, and reducing costs developed for the automobile industry would likely have marine power plant applications as well.

Integrated Electric Drive or Power Station

A term used to describe a collection of different power sources used together in an electric drive plant. For example, a gas turbine generator and two diesel generators all capable of independent or parallel operation on a main propulsion bus.

MISSION AND OPERATIONS CAPABILITY IMPACTS

Coast Guard cutters are expected to be used in a wide range of missions encompassing a variety of operating profiles. The multi-mission requirements place a premium on flexibility from the propulsion system, as well as all onboard systems. In addition, the varying roles of the future Deepwater cutter(s) will require all on board systems to be designed with an overall mission capability perspective. Mission areas and mission requirements are summarized from the Deepwater Mission Analysis Report [6] and the Functional Capabilities Specification (FCS) for the Integrated Deepwater System [7].

CURRENT MISSIONS

Maritime Law Enforcement (MLE)

The current MLE mission is comprised of three mission areas, fisheries and other living marine resources, drug interdiction, and illegal migrant interdiction. The cutter typically spends a significant amount of time patrolling at economical speed, runs at high speed to intercept a target or move between patrol areas, and operates at close to zero speed during boarding or enforcement operations. This type of profile requires a propulsion system that is capable of extended periods of low speed or idle operations, quick response from standby status to full power and machinery ratings that allow for long runs at full power.

This type of operating profile would tend to favor a combined plant or integrated electric plant where the system can be designed for good operations at low speeds as well as high speed.

For a combined plant, setting the operations envelope on the cruise plant is critical. If the cut-over speed is designed too low, the cutter will spend a significant period of time operating on the boost plant, which is typically inefficient or has detrimental maintenance implications when operating at low power levels. If the cut-over speed is designed too high, the cruise plant becomes susceptible to the same efficiency and maintenance implications of the boost plant.

An integrated electric plant would be subject to the similar design considerations for the operating envelope, but the ability to decouple the prime movers speed-power curve from the propeller speed-power curve offers additional flexibility in handling partial power operations.

As part of the MLE mission profile, the Deepwater Surface Platform is required to be able to tow vessels up to 200 ft. in length. This should not be a limiting factor in determining the installed power of the cutter, but it will have design implications. A significant concern with occasional towing is having the capability of operating slowly enough to tow safely.

The system design should take the towing speed-power curve of the vessel in to account. While the ship is towing, it will require more power and can result in operating an engine with an over rich fuel mixture, which will reduce engine life and fuel economy and increase emissions.

Vessels that tow often (such as tugboats) frequently use ducted propellers to improve performance. It is not likely that propeller ducts will be called for here since towing capability is only a small fraction of the overall mission statement, but since duct design has improved substantially in the last decade it might bear further investigation.

Maritime Safety

The current Maritime Safety mission is comprised of three mission areas, Deepwater Search and Rescue (SAR), International Ice Patrol, and Data Buoy support.

Although a slightly different operating scenario, response to Deepwater SAR would not pose any requirements on the propulsion plant beyond those outlined above. Once on scene, a propulsor capable of vectoring thrust, such as a Z-drive, pump jet or podded propulsor could be beneficial to close alongside maneuvering while rendering assistance. However, this would not be a driving requirement for the design. The requirement to tow vessels up to 3000 gross tons would be more stringent than the MLE requirement for towing 200 ft. long vessels.

The International Ice Patrol mission does not pose any design requirements on the propulsion system beyond those of the MLE mission, except the cold water and air inlet temperatures that would be expected. Operation in water with some ice cover could pose a problem for waterjet propulsion.

The Data Buoy support mission does not pose any design requirements on the propulsion system beyond those of the MLE mission.

National Defense

The current National Defense mission is comprised of three mission areas, Maritime Interception Operations, Deployed Port Operations, Security and Defense, and General Defense Operations.

As stated in [6], none of the National Defense mission areas place design requirements on the propulsion system beyond those of the MLE mission. However, General Defense Operations requirements are not well defined. If the "Disengage, evade, and avoid surface attack" requirement is expanded to include specific cutter signature limitations, there could be significant impacts to the propulsion system. The propulsion system is typically a primary source of acoustic, thermal and often visual signature. Strict acoustic signature limits

would favor fuel cells, gas turbines (to a lesser degree), and electric drive. Strict thermal signature limits would favor fuel cells.

Gas turbines present the greatest challenge in reducing infrared (IR) signature. Their higher air flow requirements, combined with a typically higher exhaust temperature present more of an IR signature than diesels, fuel cells would present a lower IR signature than diesels. IR signature is typically reduced by air cooling the exhaust pipe, shielding, or mixing ambient air with the exhaust to reduce the temperature differential with the surroundings. [8]

The requirement to minimize radar cross-section would factor against selecting a waterjet, since the jet spray can present a significant radar cross-section.

The Functional Capabilities Specification [7] outlines some requirements for a national security cutter that would have design implications for the propulsion system. Specific requirements impacting the propulsion system selection and design are speed (28 knots), endurance (12,000 NM @12 knots) and minimizing radar cross section.

The combination of 28 knot speed and 12,000 NM @ 12 knot range favors a combined plant with efficient cruise power designed around a 12 knot speed and boost capability to achieve 28 knots. Without a more specific operating profile, designers are free to assume the cutter will spend only a small portion of its operating time at speeds above cruise. This assumption favors carrying the smallest space and weight claim possible for the boost plant, making it highly likely the boost engines would be gas turbine(s). Boost transmission could be gears or electric drive. Cruise propulsion could be geared diesel, diesel-electric or fuel cells.

Marine Environmental Protection

The current Marine Environmental Protection mission is comprised of three mission areas, MARPOL Enforcement, Lightering Zone Enforcement, and Foreign Vessel Inspection.

The Marine Environmental Protection mission areas do not place design requirements on the propulsion system beyond those of the MLE mission.

POSSIBLE FUTURE MISSIONS

A number of possible future missions for the Coast Guard's Integrated Deepwater System are described in the Mission Analysis Report. The Mission Analysis Report states, "With but few exceptions, the capabilities required to carry out these future missions, and others like them, would seem to be accounted for in the functional requirements for the better defined missions discussed earlier in this report."

National Defense Operations

Possible future National Defense Operations are listed as Forward Presence, Surveillance, Convoy Escort, Mine Warfare, and Post Conflict Peacebuilding. A mine warfare mission could have underwater acoustic signature requirements that would impact the propulsion system design, but the other missions would not place limiting design constraints on the propulsion system. Sustained on scene endurance is mentioned in several of the missions, so low fuel consumption would be desirable, but without a specific requirement, it would not restrict the propulsion plant design beyond the operational cost considerations that are already present.

Marine Resources and the Environment

Potential missions in support of marine resources and the environment are listed as UN/International Operations, Non-living Marine Resources, and Oceanographic Data Collection and Survey. As with National Defense Operations, a sustained endurance capability is mentioned, but the comment from above applies.

In the Non-living Marine Resources discussion of [7], the potential for a submarine capability is mentioned. A submersible would place a number of design constraints on the propulsion system. An electric drive would be expected and fuel cells would become an attractive power source. However, since there is no firm requirement for a submersible as part of the Integrated Deepwater System, it is unlikely an industry team would propose one.

As described, the potential Oceanographic Data Collection and Survey mission would not present any limiting design criteria on a propulsion system design.

Disaster and Terrorism Response and Protection

The potential Disaster and Terrorism Response and Protection mission does not pose any specific design constraints on the propulsion system. The desired capability to provide electrical power to a small city would favor an integrated electric drive propulsion system. However, without a firm requirement this would not drive the design decision.

HULL FORM IMPACTS

The hull form selected for any vessel will typically carry with it design implications for the propulsion system. The most obvious hull form impact is the space and weight claim for the propulsion system components and the fuel load required for the specified mission.

A system's total space and weight claim, including fuel load, is a very important design trade off. Typically, fuel efficiency is inversely related to the size and weight of the machinery, i.e. larger medium speed engines tend to be more fuel efficient than high speed engines, which tend to be more fuel efficient than gas

turbines. This trend is countered by the power density increase from medium speed engines, to high speed engines, to gas turbines. Because of this, for a given mission payload of crew, small boats, and other outfit a gas turbine powered ship can be smaller than an equivalent diesel powered ship. Alternatively, for the same hull, a gas turbine power plant may allow for more mission payload.

Arrangements are another key interaction between the hull form and propulsion plant. Gear driven or direct drive systems require the engine(s), transmission, and propulsor shaft to be carefully aligned. The designer has little flexibility in where the propulsion machinery can be located. This can be especially restrictive in SWATH or other multi-hull arrangements where the narrow hull sections can restrict what power sources will fit in the ship. Electric drive offers significant advantages in arrangement flexibility since the generators or fuel cells can be placed nearly anywhere on the ship. For example, USCGC HEALY has the engine room on the main deck.

The propulsor also has several design interactions with the hull form. Z-drives and podded propulsors allow the stern lines to be free from shaft bossings, struts, and other shafting appendages. This can allow for improved hydrodynamic flow. As a trade-off, these propulsors require a flat section of hull bottom and some stern overhang.

Controllable-reversible pitch propellers and contra-rotating propellers require larger shaft diameters, increasing the interference potential in way of the shafting.

Waterjets are normally installed with the exit nozzle ventilated for best performance. This restricts installation of the jet to near the waterline. Depending on hull form, there can be a significant space and volume of inlet ducting with the jet, or the aft hull lines may be impacted to suit the installation of the jet.

TOP SPEED REQUIRED

A vessel's top speed requirement is one of the most, if not the most, significant performance parameters impacting propulsion system design. The power required for top speed is the most obvious design requirement, maneuvering or towing speed requirements can also impact the design.

At top speeds that would be expected for a Coast Guard cutter (~25+ knots), required power for most hull forms follows a cubic relationship with speed.

The power required to increase top speed from V1 to V2 can be approximated by:

$$P2/P1 = (V2/V1)^3$$

Where P1 is the power required going V1 and P2 is the power required going V2. For example, if a top speed requirement goes from 24 knots to 30 knots, the required power nearly doubles. Since most propulsion system component acquisition and life cycle costs are roughly proportional to power, those costs would also be expected to double. Using the same relationship, an increase in required top speed from 28 knots to 33 knots would result in roughly a 65% increase in installed power, with a similar increase in acquisition and life cycle costs.

An increase in power would also require either an increase in space and weight claim for the propulsion system or selection of a system with higher power density, which normally implies higher acquisition and life cycle cost.

Since engines have a lower limit for their operating speed, a gear drive system with fixed pitch propellers will also have some minimum speed the vessel can make. As a rough estimate, the minimum operating speed of an engine can be assumed to be 1/3 to 1/2 the maximum operating rpm. This means a 30 knot vessel could have a minimum speed of ~10 – 12 knots unless equipped with controllable pitch propellers, a trolling gear, electric drive or some other speed control in either the transmission or propulsor.

It is impossible to identify a specific speed that would require a designer to use gas turbines in the propulsion system. However, it is worth noting that virtually every naval ship in the world of WMEC or larger size with a top speed of over 30 knots includes gas turbines in the propulsion system [1].

OTHER SYSTEM IMPACTS

The two systems most significantly affected by the propulsion system design are the ship's service electrical system and steering system.

With an integrated electric drive system, ship's service and propulsion power are both fed from a common source. The overall system impacts are substantial. The main generators will be sized larger than if they were for propulsion power only and there will be no dedicated ship's service generators. There is typically still an emergency or auxiliary generator set which may or may not be part of the propulsion loop. This results in a smaller number of engines in the ship, but may increase the complexity of the electrical system. The smaller number of engines, and typically lower total installed horsepower, partially offsets the increased acquisition cost for the electric drive machinery. The frequency conversion equipment required for the propulsion motors can alter the waveform of the main power, requiring sensitive equipment to be fed from a motor-generator set or other 'clean' power source. A significant advantage is the plant's ability to

handle large loads such as hoists, windlasses, boat davits etc. Since the plant is sized for propulsion loads, even large auxiliary loads are handled without significant spikes or other disruptions to the ship's electrical supply.

Z-drives, podded propulsors, waterjets, and pumpjets all are capable of vectoring thrust which eliminates the need for conventional rudders and steering gears. In most installations, these types of propulsors offer improved maneuverability and stopping ability compared to conventional or controllable-reversible pitch propellers. Z-drives, podded propulsors, and pumpjets are typically installed with the ability to rotate through 360 degrees allowing full thrust to be provided in any direction. Waterjets are normally fitted with buckets that deflect the water stream to produce steering and reversing forces.

The cost of these types of propulsors needs to be compared to the cost of both propulsion and steering systems in conventional designs. In addition, the appendage drag from the rudders is eliminated along with the rudder and steering gear space and weight claim.

Propulsion system impacts to other ship systems and functions are primarily related to the air intake, exhaust and cooling water systems.

Air intake and exhaust plenums, ducts, stacks, etc. compete for valuable topside space with flight decks, antennae, boat decks, etc. Although not typically limiting factors, the high airflow requirements of a gas turbine can aggravate the design problem and the arrangements flexibility of an electric plant can help mitigate a problem by offering more choice in where the intake and exhaust systems are run. Stern exhaust, side exhaust and underwater exhaust are all possible options to limit the deck space claim of an exhaust system. All add complexity, since means must be provided to prevent water from traveling up the exhaust pipe to the engine.

Propulsion cooling system design needs to consider boat operations. Overboard discharges need to be located away from the area where boats are expected to come alongside. Keel coolers and box coolers eliminate the need for overboard discharges and seawater pumps and piping, but may involve additional hull penetrations or have problems providing cooling when the ship is stationary. Gas turbines simplify the cooling system since the engine has no cooling water requirements. Diesel engines would have the highest cooling water requirements. Gears and electric transmissions can both require cooling water, but requirements are minimal.

LIFE CYCLE IMPACTS

ENVIRONMENTAL

None of the candidate systems are expected to have any difficulty meeting proposed International Maritime Organization pollution standards. Engine manufacturers will be required to meet those standards for all customers, and many are claiming compliance with proposed standards today.

Power sources are the primary contributors to environmental emissions. Fuel cells would be the lowest emission power source available. Gas turbines offer lower NOX and particulate emissions than diesels, but the higher specific fuel consumption of a turbine partially offsets that advantage.

Sulfur oxide (SOX) emissions from diesels and gas turbines are largely a function of the sulfur content of the fuel. The fuel reformation process required for a fuel cell would remove the sulfur, but may produce waste by products that need to be dealt with.

Controllable-reversible pitch propellers are a possible source of pollution. Oil seal failure is the concern, when operating properly the pitch control system does not emit any oil. Oil seals could be a concern for Z-drives or podded propulsors.

SUPPORTABILITY

Of the candidate propulsion components, only fuel cells are not currently available marine technology supported commercially and/or by the Federal Supply System. Waterjets in the power range expected for a Deepwater cutter, podded propulsors, pumpjets, and many of the potential electric drive components are technology that does not currently exist in the US Coast Guard or Department of Defense and is not supported by the Federal Supply System. A number of the candidate systems are produced by European companies, but most have licensing and/or support agreements with North American firms.

CREWING

Crew size is determined predominantly by mission needs, damage control/emergency response requirements and organizational maintenance philosophy. The engineering department of most Coast Guard cutters represents 30-40% of the crew, with roughly one-third of the engineering department assigned to the main propulsion division. Therefore, the specific propulsion system selected impacts only a small fraction of the crew.

The system selected would have some impact on the make-up of the engineering department. An integrated electric drive would be likely to have more electricians and fewer machinery technicians because of the increased complexity of the electric plant and the fewer total number of prime movers.

Since it is technically feasible to design any of the candidate propulsion systems to operate with unmanned engineering spaces, the propulsion system selected would not be a driving factor in determining crew size. That doesn't mean an automated propulsion system is an optimum solution, only that it is feasible.

The limiting factor on crew size is likely to be performing operational missions. As a hypothetical example, a cutter designed to be able to conduct at least two law enforcement boardings simultaneously would need a crew sized for at least two boarding parties, boat handling operations, cutter navigation, and communications. Taking a typical percentage of engineers that would provide more than enough people for operation and underway maintenance of any of the candidate propulsion systems.

LIFE CYCLE COSTS

The life cycle cost of any system is made up of it's acquisition costs, operating and routine maintenance costs, and any scheduled replacement or upgrade expenses.

Acquisition cost is a one time expense unless a system component has a scheduled replacement during the cutter's service life. Of the candidate propulsion system components, only fuel cells would have a requirement to be replaced during a 30 year cutter service life. Although, any of the components could be replaced as part of a major renovation should the needs of the service dictate. Table 4 lists rough parametrics which can be used to estimate costs of various components. For the purposes of this system model, components are assumed to have fairly linear costs on either a per horsepower or per weight basis. It should also be noted that without a hull form point design, speed requirements and some systems arrangement, these estimates could vary widely.

Operating and maintenance (O&M) expenses are a function of either calendar time or operating hours. Fuel, lube oil, preventive maintenance, repairs and scheduled overhauls are the significant drivers for these expenses. These expenses are predominantly a function of the power source, although the efficiency of other drive train components obviously factors in to fuel consumption. With the exception of controllable pitch propellers, transmission and propulsor systems tend to be very low maintenance equipment. Controllable pitch propellers are known to occasionally require seal maintenance, which can involve the expense of unscheduled dry-docking.

Fuel costs are typically the dominant component of propulsion system O&M expenses. Maintenance expenses tend to be roughly proportional to installed horsepower of the ship and operating profile (power-hours). Other differences between power sources tend to have mitigating counter points. For example, gas turbines tend to have shorter overhaul intervals than diesel engines, but the ease of removing and reinstalling a turbine allows for a very short cutter down

time (assuming a spare engine is available) and the overhaul can be performed under controlled shop conditions.

Maintenance costs for fuel cells in a marine environment are an unknown. Their lack of moving parts and history in shore based power plants support the assumption that maintenance costs would be lower than for diesels or gas turbines. The life cycle cost of a fuel cell plant will include at least one cell replacement during a typical Coast Guard cutter life cycle.

Table 4. Acquisition Cost Estimates

Subsystem	**Acquisition Cost Range**
Medium Speed Diesels	~$225/BHP
High Speed Diesels	~$175/BHP
Gas Turbines	~$400/BHP*
Fuel Cells	~$1200/BHP (could vary widely)
Reverse Reduction Gear	~$180/BHP **
Reduction Gear	~$150/BHP **
Electric Drive (generators, motors and conditioning equipment)	~$400/BHP
Z-Drive	~$500/BHP (includes propeller)
Direct Drive	~$25/BHP
Fixed Pitch Propellers	~$20/lb
Controllable Reversible Propellers	~$40/lb
Contra Rotating Propellers	~$20/lb
Waterjet	~$80/BHP
Pump Jet	~$320/BHP
Podded Propulsor	~$550/BHP (includes motor)

**An exception to gas turbine pricing is the GE LM2500, which has an acquisition cost per BHP comparable to medium speed diesels. A logical explanation is the large population of this engine in the U.S. Navy inventory.*

***Gear price estimates vary widely and are only based on a few data points. A number of factors, such as operating RPM, gear complexity, and power levels are key to gear price (and weight). [9] evaluates a number of destroyer and amphibious ship point designs, in that study gear drive systems have gear cost estimates roughly comparable to the cost estimates for the prime movers.*

SUMMARY AND CONCLUSIONS

Proteus Engineering was tasked by the Marine Systems & Environmental Technology Division, U.S. Coast Research and Development Center, to investigate propulsion systems that may be candidates for the Coast Guard's Deepwater Surface Platform.

This report and the attached component information sheets outline the significant characteristics, advantages and disadvantages of the candidate propulsion system components.

The study also included a review of the Deepwater Capability Replacement Project Mission Analysis Report and Functional Capabilities Specification for requirements that would restrict or drive the design of the Deepwater cutter(s). There are no requirements that would eliminate any of the candidate components from being part of a cutter propulsion system. The strongest design driving requirement is the combination of speed (28 knots) and range at cruising speed (12,000 nm @ 12 knots) for the national security cutter would favor, but not require, some type of combined plant with gas turbines providing boost power. No requirements were noted that would be unduly restrictive on the propulsion plant design.

The important consideration in designing the propulsion system is that the design team consider all the implications of the system(s) selected and not focus solely on any one performance or cost parameter. For example, the high power density of a gas turbine may allow more space and weight to be available for mission equipment – the increased mission capabilities offered by that trade off could offset the higher fuel consumption of the turbine, resulting in a lower overall system life cycle cost.

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APPENDIX A: SYSTEM MODEL DESCRIPTION

To assist G-ADW in analyzing the variety of propulsion system options, a model was developed in MS Excel to quickly calculate rough estimates of annual fuel consumption, system space claim, and weight claim. This model was developed for Coast Guard (G-ADW) in-house use only. Model validation and enhancement efforts are underway as a follow-on task to Proteus Engineering.

The model requires the user to select component options for propulsor, transmission, and power source, enter the effective horsepower required for cruise speed and full speed, the estimated operating hours per year and select an operating tempo.

Upon opening the workbook, the user will see the output and control screen (Figure 1).

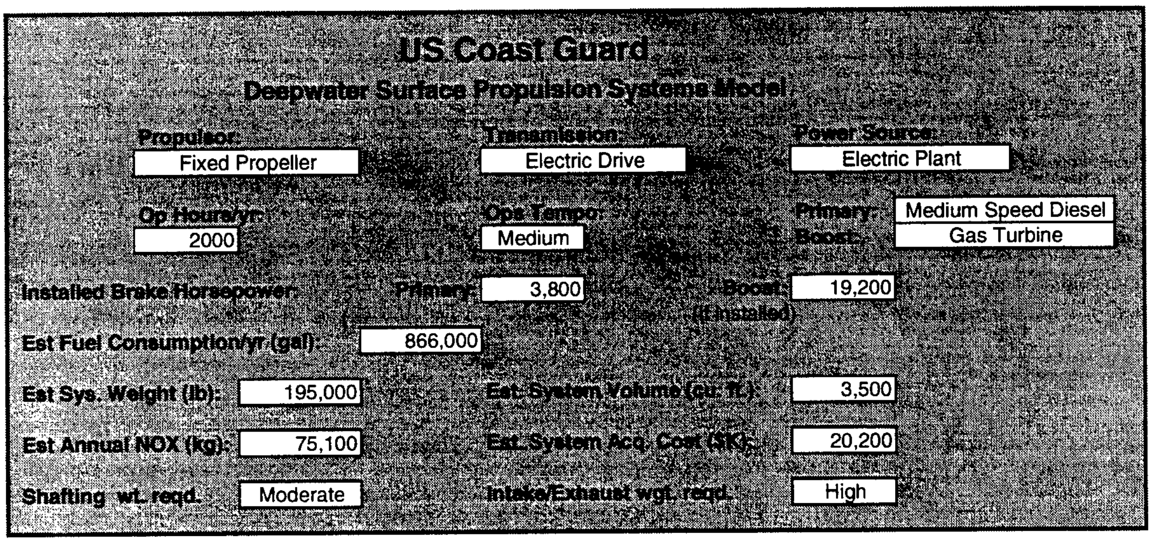

Figure 1. Propulsion Model Output Screen

Clicking on the "Run Model" button brings up the input dialog box (Figure 2). From that box, the user makes component selections and enter powering and operating data required by the model.

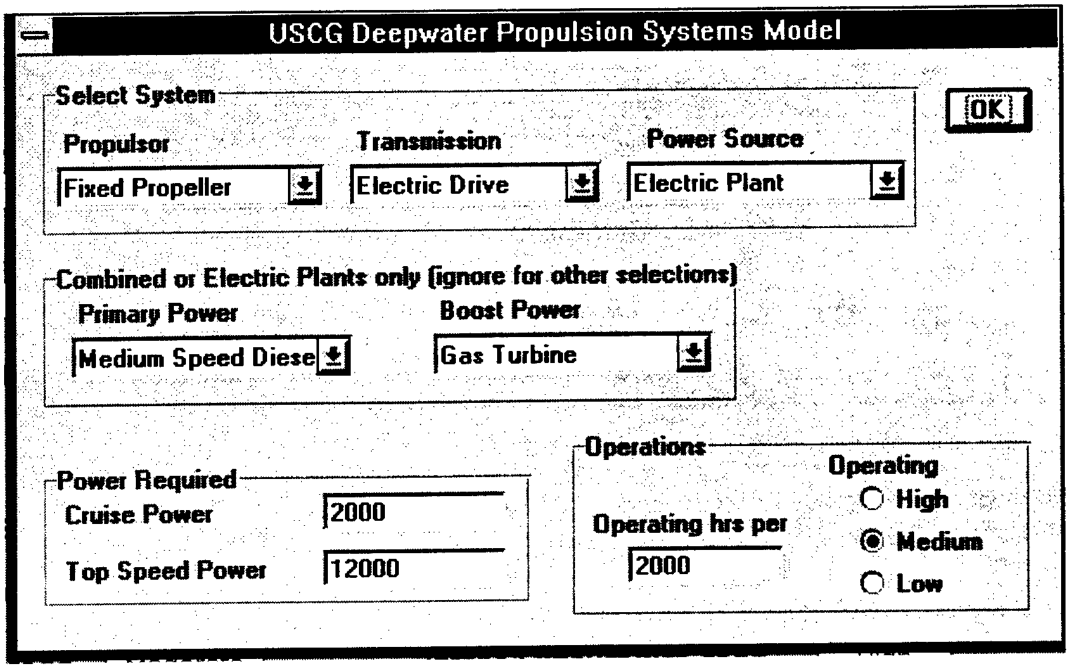

Figure 2. Dialog Box

From the input boxes, the user selects propulsor, transmission and power source from drop down lists. If a hybrid (combined 'and' or combined 'or') plant or electric plant are selected, the user also chooses power sources for primary and boost power from drop down lists. The 'Primary Power Source' and 'Boost Power Source' selections are ignored unless a hybrid plant is chosen. If a hybrid plant is chosen and primary and boost selections are not made, the model defaults to medium speed diesel for primary power and gas turbine for boost power.

The model also needs the effective horsepower for cruise speed and top speed. Note this entry is the effective horsepower for the hull form, not the installed brake horsepower. The model uses estimates of propulsor efficiency and transmission efficiency to calculate installed brake horsepower (BHP). The BHP also uses a service factor of 85%, i.e. under trial conditions, rated top speed should be achieved using 85% of installed propulsion power. The installed power presented on the output sheet will be substantially higher than the effective power entered in the input box. The model uses the cruise effective horsepower with primary power source parameters and full speed horsepower with primary and/or boost power parameters to calculate fuel consumption and NOx emissions estimates.

The remaining entries are an estimate of the cutter operating hours per year and selection of an operating tempo.

The operating tempo defines the percentage of operational time the cutter is projected to spend at full power, cruise speed and loitering. Those settings are:

High – Full – 50%, Cruise – 40%, Loiter – 10%

Medium – Full – 30%, Cruise – 40%, Loiter – 30%

Low – Full – 10%, Cruise – 60%, Loiter – 30%.

By using representative values for efficiencies, fuel consumption, space and weight claims for the selected systems, rough estimates are calculated for projected annual fuel consumption, system weight, system volume, annual NOX emissions, and a rough order of magnitude acquisition cost estimate for the propulsor, transmission and power source.

The model makes a relative 'high, moderate, low' comment on the weight of shafting, intakes and exhaust runs. Since shaft lengths, intake and exhaust runs are highly dependent on hull form and arrangements, even rough numeric estimates of the space and weight claims add little value unless a design concept is available.

The output sheet can be printed from the File – Print menu since the user is in MS Excel. Copying the sheet and pasting it to another workbook can save output sheets.

Because weight, space and cost figures can vary widely depending on features required, arrangements, manufactures scope of supply, etc., values calculated by the model are best used for relative comparison between systems, not as an absolute estimate of a cutter's propulsion system cost.

APPENDIX B

COMPONENT DESCRIPTION SHEETS

Propulsors	FPP	CRP	Contra	WaterJet	PumpJet	Pod
Power Range Available						
Speed Range Available						
Efficiency	0.68	0.66	0.75	0.55	0.65	0.71
Lube Oil cons (g/kW-hr)			0	0		
Power density						
Power/weight (kg/kW)				1.6	11.7	16
Power/volume (m^3/kW)	0		0	0.003	0.015	0.002

Transmissions	Rev Gear	Gear	Z-Drive	Electric	Direct
Power Range Available					
Efficiency	0.96	0.97	0.96	0.9	0.99
Lube Oil cons (g/kW-hr)					
Power density					
Power/weight (kg/kW)	2.35	2	11	7.5	
Power/volume (m^3/kW)	0.0023	0.002	0.0045	0.008	

Power Sources	Med	High	MGT	Fuel Cell
Power Range Available				
Fuel consumption (g/kW-hr)	193.07	195.898	245	148
Lube Oil consumption (g/kW-hr)				
Power density				
Power/weight (kg/kW)	8.085709	6.103516	0.2	20
Power/volume (m^3/kW)	0.012089	0.00862	0.001	0.035
NOX Emissions (g/kg of fuel)	60	45	15	2.5

Fixed Pitch Propeller	Low End	High End
Power Range Available	Covers the full operating range expected for a Deepwater cutter.	
Speed Range Available	Covers the full operating range expected for a Deepwater cutter.	
Efficiency	0.65	0.72
Lube Oil consumption (g/kW-hr)	0	0
Power density		
Power/weight (kg/kW)	Power density is not linear with power	
Power/volume (m^3/kW)		

A fixed pitch propeller's only life cycle costs are the initial acquisition costs and any repairs due to damage. There is no routine maintenance or need to replace the unit due to wear-out.

There is no space claim inside the ship for the propeller, but the lines in the stern need to allow for propeller installation.

Because there are no parts to wear, a fixed pitch propeller's reliability is excellent. The only failure mode is damage due to impacts. Fouling with lines or nets may require maintenance action to clear the propeller(s), but does not typically damage them.

Controllable-Reversible Pitch Propeller	Low End	High End
Power Range Available	Covers the full operating range expected for a Deepwater cutter.	
Speed Range Available	Covers the full operating range expected for a Deepwater cutter.	
Efficiency	0.63	0.7
Lube Oil consumption (g/kW-hr)	0	0
Power density	Power density is not linear with power	
Power/weight (kg/kW)		
Power/volume (m^3/kW)		

A controllable pitch propeller's life cycle costs are the initial acquisition costs, routine maintenance of the hydraulic and control system, make up hydraulic fluid and any repairs due to damage. Initial acquisition costs are substantially higher than for fixed pitch propellers because of the hydraulics, controls, and more complicated production processes. Routine maintenance is typically checking fluid levels, and replacing fluid filters.

The hydraulics for pitch acutation and control will have a space claim in the ship and the lines in the stern need to allow for propeller installation.

Controllable pitch propellers are proven, reliable pieces of equipment. Common failure modes are seal leakage and damage due to impacts. Fouling with lines or nets may require maintenance action to clear the propeller(s), and may damage the seals between the hub and blades.

Contra-Rotating Propeller	Low End	High End
Power Range Available	Covers the full operating range expected for a Deepwater cutter.	
Speed Range Available	Covers the full operating range expected for a Deepwater cutter.	
Efficiency	0.6	0.7
Lube Oil consumption (g/kW-hr)	0	0
Power density		
Power/weight (kg/kW)	Power density is not linear with power	
Power/volume (m^3/kW)		

Contra-rotating propeller's only life cycle costs are the initial acquisition costs and any repairs due to damage. There is no routine maintenance or need to replace the unit due to wear-out. Acquistion costs would be higher than for fixed pitch propellers since there are two propellers per shaft and the shafting is more complicated and the gears or motors driving the propellers are more complex than other systems.

There is no space claim inside the ship for the propeller, but the lines in the stern need to allow for propeller installation. Since there are two propellers per shaft, the propeller diameters can be smaller than fixed pith propellers for the same power.

Because there are no parts to wear, a fixed pitch propeller's reliability is excellent. The only failure mode is damage due to impacts. Fouling with lines or nets may require maintenance action to clear the propeller(s), but does not typically damage them.

Waterjet	Low End	High End
Power Range Available	Covers the full operating range expected for a Deepwater cutter.	
Speed Range Available	Covers the full operating range expected for a Deepwater cutter.	
	although not very efficient for lower speeds (<20 knots).	
Efficiency	0.5	0.6
Lube Oil consumption (g/kW-hr)	0	0
Power density		
Power/weight (kg/kW)	1.4	2
Power/volume (m^3/kW)	0.002	0.004

A waterjet's only life cycle costs are the initial acquisition costs and any repairs due to damage. There is no routine maintenance or need to replace the unit due to wear-out.

There can be significant space claim inside the ship for the waterjet, and the nozzle typically needs to be installed near the waterline, which can result in a long inlet duct run.

From a maintenance standpoint, the seals and bearings of a waterjet are comparable to shaft seals and bearings for a propeller system. The only failure mode is damage due to impacts or ingestion of debris. Fouling with lines or nets may require maintenance action to clear the impeller(s), but does not typically damage them. Since the waterjet is essentially a high volume pump, it can be susceptible to debris ingestion. Waterjets are often installed with reversing gears in order to backflush the pump to clear debris.

Pump Jet	Low End	High End
Power Range Available	65	3000
Speed Range Available	0	20 knots
Efficiency	0.6	0.7
Lube Oil consumption (g/kW-hr)	0	0
Power density		
Power/weight (kg/kW)	10	12
Power/volume (m^3/kW)	0.01	0.02

A pumpjet's only life cycle costs are the initial acquisition costs and any repairs due to damage. There is no need to replace the unit due to wear-out, although the azimuthing (steering) gears may require occasional lubrication.

There can be significant space claim inside the ship for the pumpjet. Since the inlet and exit are flush mounted, the hull shape can be optimized to reduce hydrodynamic resistance.

From a maintenance standpoint, the seals and bearings of a pumpjet are comparable to shaft seals and bearings for a propeller system. The only failure mode is damage due to impacts or ingestion of debris. Fouling with lines or nets may require maintenance action to clear the impeller, but does not typically damage it. Since the pumpjet is essentially a large pump, it can be susceptible to debris ingestion, although the centrifugal pump of a pumpjet would be less susceptible to fouling then a waterjet..

Podded Propulsor	Low End	High End
Power Range Available	0.5MW	14MW
Speed Range Available	0	22+ kts
Efficiency	0.68	0.75
Lube Oil consumption (g/kW-hr)	0	0
Power density		
Power/weight (kg/kW)	14	18
Power/volume (m^3/kW)	0.0015	0.0025

A podded propulsor's only life cycle costs are the initial acquisition costs, any repairs due to damage and maintenance of the electric motor. AC electric machinery is typically very low maintenance. The azimuthing (steering) gears may require occasional lubrication. The pods can be fitted with propellers on both ends, which may be contra-rotating. The large pod containing the motor would increase drag, however that is offset by not having rudders or shaft struts in the flow pattern.

There is some space claim inside the ship for the mounting hardware, slip ring and azimuthing mechanism. There is more flexibility in designing the hullform than with a shafted propeller system, since there is no need to accomodate the shafting and struts.

Electric podded propulsors are relatively new technology, but they have been proven in icebreaker service. Life cycle maintenance would be expected to be very low.

Reverse Reduction Gears	Low End	High End
Power Range Available		10000 kw
Efficiency	0.95	0.97
Lube Oil consumption (g/kW-hr)	0.05	0.05
Power density		
Power/weight (kg/kW)	2	2.7
Power/volume (m^3/kW)	0.0021	0.0027

A reverse reduction gear's only life cycle costs are the initial acquisition costs, and occaisional inspection, lube oil makeup and filter changes.

The space claim is fairly small, but placement and alignment with the propulsion shaft and engine are critical.

Acquisition costs dominate the overall life cycle cost of a reverse reduction gear system.

Reduction Gears	Low End	High End
Power Range Available	Covers the full operating range expected for a Deepwater cutter.	
Efficiency	0.96	0.98
Lube Oil consumption (g/kW-hr)	0.05	0.05
Power density		
Power/weight (kg/kW)	2	2.7
Power/volume (m^3/kW)	0.0021	0.0027

A reduction gear's only life cycle costs are the initial acquisition costs, and occaisional inspection, lube oil makeup and filter changes.

The space claim is fairly small, but placement and alignment with the propulsion shaft and engine are critical.

Acquisition costs dominate the overall life cycle cost of a reduction gear system.

Z-Drive	Low End	High End	
Power Range Available	1200	6000	
Speed Range Available	0	20 knots	
Efficiency	0.95	0.97	(not including propeller)
Lube Oil consumption (g/kW-hr)	0.05	0.05	
Power density			
Power/weight (kg/kW)	8	12	
Power/volume (m^3/kW)	0.004	0.005	

A Z-Drive's only life cycle costs are the initial acquisition costs, any repairs due to damage and maintenance of the gear train. Gears are typically very low maintenance. The azimuthing (steering) gears may require occasional lubrication. The drive can be fitted with propellers on both ends, which may be contra-rotating. The appendage containing the gear train would increase drag, however that is offset by not having rudders or shaft struts in the flow pattern.

There is some space claim inside the ship for the mounting hardware, slip ring and azimuthing mechanism. There is more flexibility in designing the hullform than with a shafted propeller system, since there is no need to accomodate the shafting and struts.

The additional cost of Z-drives is partially offset by eliminating the need for rudders and steering gear.

AC-AC Electric Drive	Low End	High End
Power Range Available	Covers the full operating range expected for a Deepwater cutter.	
Efficiency	0.85	0.9
Lube Oil consumption (g/kW-hr)	0	0
Power density		
Power/weight (kg/kW)	7	8
Power/volume (m^3/kW)	0.007	0.01

An electric drive's only life cycle costs are the initial acquisition costs, and occaisional inspection, and cleaning.

The space claim is fairly small, but placement and alignment with the propulsion shaft and engine are critical. However, since there is no mechanical connection between the power source and propulsor, the generator set can be located virtually anywhere in the ship. This provides the designer considerable arrangements flexibility. Ship construction costs may also be reduced because of flexibility is scheduling machinery installation and elimination of the complicated alignment process.

Direct Drive	Low End	High End
Power Range Available		
Efficiency	near 1.0	
Lube Oil consumption (g/kW-hr)	0	0
Power density		
Power/weight (kg/kW)	None beyond shafting and couplings.	
Power/volume (m^3/kW)		

A direct drive's only life cycle cost is the acquisition of the shafting and couplings. Maintenance is virtually nonexistent.

The space claim is very small, but placement and alignment with the propulsion shaft and engine are critical. Space and weight claim depend on the distance between the engine and propulsor and are strictly a function of the shaft size and material. With some of the lighter weight, composite shafts on the market, weight claim could be treated as near zero for a rough order estimate like this one.

Direct drive requires a near exact match between the engine and propulsor power characteristics. It also requires a reversible propulsor for the power sources likely to be considered for the Deepwater cutter(s).

Medium Speed Diesel	Low End	High End
Power Range Available		
Fuel consumption (g/kW-hr)	189	197
Lube Oil consumption (g/kW-hr)	0.5	0.5
Power density		
Power/weight (kg/kW)	5.2	11
Power/volume (m^3/kW)	0.008	0.015

A diesel's life cycle costs are the initial acquisition costs, fuel consumption, preventive maintenance, scheduled overhauls, repairs, and lube oil consumption. Fuel makes up the largest portion of the operating and maintenance expenses.

The space and weight claim vary widely, predominantly dependent on the operating RPM of the engine.

Electronic control of fuel injection, engine monitoring and diagnostics are becoming common place and will be widely available across all ranges of engine power lines by the time the Deepwater cutter systems design is complete.

High Speed Diesel	Low End	High End
Power Range Available		
Fuel consumption (g/kW-hr)	188	215
Lube Oil consumption (g/kW-hr)	0.5	0.5
Power density		
Power/weight (kg/kW)	4.15	8.4
Power/volume (m^3/kW)	0.0055	0.014

A diesel's life cycle costs are the initial acquisition costs, fuel consumption, preventive maintenance, scheduled overhauls, repairs, and lube oil consumption. Fuel makes up the largest portion of the operating and maintenance expenses.

The space and weight claim vary widely, predominantly dependent on the operating RPM of the engine.

Electronic control of fuel injection, engine monitoring and diagnostics are becoming common place and will be widely available across all ranges of engine power lines by the time the Deepwater cutter systems design is complete.

Gas Turbine	Low End	High End
Power Range Available		
Fuel consumption (g/kW-hr)	230	260
Lube Oil consumption (g/kW-hr)	0.5	0.5
Power density		
Power/weight (kg/kW)	0.19	0.2
Power/volume (m^3/kW)	0.0006	0.001

A turbine's life cycle costs are the initial acquisition costs, fuel consumption, preventive maintenance, scheduled overhauls, repairs, and lube oil consumption. Fuel makes up the largest portion of the operating and maintenance expenses.

The space and weight claim are the significantly less than any of the other candidate power sources.

The U.S. Navy ICR turbine program is progessing and may be available by the 2002 timeframe. The ICR turbine claims to reduce fuel consumption by ~27%. Weight and space claim would approximately double over simple cycle turbines. Acquisition costs are difficult to predict at this time, but expect an ICR turbine would cost 50-100% more than a simple cycle turbine.

Fuel Cell	Low End	High End
Power Range Available		
Fuel consumption (g/kW-hr)	148	160
Lube Oil consumption (g/kW-hr)		
Power density		
Power/weight (kg/kW)	16	40
Power/volume (m^3/kW)	0.008	0.02

A fuel cell's life cycle costs are the initial acquisition costs, fuel consumption, preventive maintenance, and a likely replacement required during the lifecycle of a cutter.

There are no marine applications of fuel cells, so the maintenance costs associated with them in the marine environment are largely unknown. Based on commercial power plant experience, maintenance costs should be very low.

Significant advantages are good fuel efficiency, very quiet operation, and very low emissions. Technical challenges are power density, reforming marine diesel fuel for use in a fuel cell, and operating in a marine environment.

It is not likely the technology will be mature for marine applications by the 2002 timeframe, but fuel cells are possible for cutters procured later than that.